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Aircrew-Vehicle System Interaction

An Evaluation of NASA's Program in Human Factors Research



Aeronautics and Space Engineering Board

Committee on Human Factors and Mechanical Systems

National Research Council

Aircrew-Vehicle System Interaction

An Evaluation of NASA's Program in Human Factors Research

Report of the ad hoc Committee on
Aircrew-Vehicle System Interaction

Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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PREFACE

NASA's role relating to human factors in aviation is found in its charter*:

- o To direct and exercise control over the research into and the solution of problems of flight within and outside the earth's atmosphere;
- o To improve the usefulness, performance, speed, safety, and efficiency of aeronautical vehicles;
- o To preserve the role of the United States as the leader in aeronautical science and technology.

Since the end of World War II, NASA and its predecessor, the National Advisory Committee for Aeronautics, have recognized the critical importance of man-machine interaction in the increasingly complex high technology aviation system. NASA's primary concern in human factors has been with the application of scientific knowledge and fundamental study, rather than with developmental or design problems.

NASA initiated a human factors research program at its Ames Research Center in the 1950s, concentrating on pilot aircraft control functions, and the present Human Factors in Aviation Safety research program began in 1973. Today, NASA's program is focused in two areas--Flight Management and Simulation Technology.

During the last decade, the emphasis of NASA's human factors program has shifted from aircraft control to the perceptual and cognitive skills necessary for effective decision making.

*U.S. Senate Committee on Commerce, Science, and Transportation. Committee Print. National Aeronautics and Space Act of 1958, as Amended, and Related Legislation. 95th Congress, 2nd Session. Washington, U.S. Government Printing Office. December 1978.

The study of human factors in flight management is guided in part by an aviation safety reporting system that provides evidence of deficiencies in the aviation system that relate to the management of information among the various system components. NASA's Aviation System Reporting System (ASRS) was initiated five years ago at the request of the aviation community and the FAA to collect data regarding operating problems and human errors in the aviation system. Hypotheses based on these data underlie much of NASA's human factors research and serve to illuminate the problems on which work is most urgently needed. The system has provided data and analytical studies for over 30 other agencies and organizations within and outside of the government, and its methods are under study for possible adoption by other nations.

NASA's Human Factors and Simulation Technology program covers research in all aspects of simulation, including hardware and software improvement, computer configuration, improved visual cue generation, optimal controlling methods of the pilot simulator system, and training methodology for making maximum use of the available simulation technology.

NASA's capability in aeronautical human factors is enhanced by:

1. Close ties with all elements of the aviation community through the formal mechanism of its advisory committee structure and informally through contacts with DOD, FAA, air carriers, aviation manufacturers, and user groups;
2. The availability of facilities important to human factors, including the Flight Simulator for Advanced Aircraft and the Vertical Motion Simulator at Ames, and the Differential Maneuvering Simulator at Langley;
3. NASA's status as an independent government agency that can act as an objective third party and its history of responsiveness to the needs of the aviation community;
4. A cadre of experienced human factors investigators that, along with supporting staff, constitutes a group dedicated to finding solutions to human factors problems in aviation.

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SUMMARY CONCLUSIONS AND RECOMMENDATIONS

The committee has reviewed NASA's program of research in human factors in the aircraft cockpit and a proposed program augmentation.

In the committee's judgment the dramatic growth of microprocessor technology makes it entirely feasible to automate increasingly more functions in the aircraft cockpit; the promise of improved vehicle performance, efficiency, and safety through automation makes highly automated flight inevitable. However, the committee believes that an organized data base and validated methodology for predicting the effects of automation on human performance and thus on safety are lacking and is concerned that without such a data base and validated methodology for analyzing human performance, increased automation may introduce new risks.

The committee concludes that NASA's effort should be concentrated on developing methods and techniques for analyzing man-machine interactions, including human workload and prediction of performance and assessment of their effects on safety and reliability. Therefore, the committee recommends that NASA, in its program of research, concentrate on providing a methodology for accomplishing a predictive human performance failure modes hazards analysis that could be integrated with the methodology used for the failure hazards analysis of hardware to provide an overall system (man and machine) hazards analysis methodology. In the committee's view, a comprehensive research effort will be required to provide a data base to support such a safety and reliability analysis methodology.

The committee further recommends that the proposed program augmentation dealing with the allocation of functions to man and machine should concentrate on the acquisition of principles and the development of methodologies of general applicability, leaving the formulation of specific guidelines for the design of interfaces between man and machine to the industry.

The committee also reviewed the research and technology development programs in aircrew-vehicle interaction in the Department

of Defense and the Federal Aviation Administration in light of NASA's ongoing and planned program. The committee concludes that NASA and DOD programs are as well coordinated and mutually supportive as can practically be achieved. It notes that the FAA's Office of Engineering and Development recognizes that much of the human factors research and development needed to meet its responsibilities is addressed in programs being conducted by NASA and the DOD, and continually draws upon the expertise and capabilities of those agencies.

The committee notes that many aircraft accidents and incidents are determined to have been caused by human error and points to the importance of determining the causes of the human error. Such information is absent in records of accident investigations. Thus, the committee recommends that NASA explore the feasibility of establishing a program to identify and evaluate the cause of the human error where it is deemed to be causal in an accident or incident situation and, if feasible, undertake such a program.

INTRODUCTION

Safety statistics indicate that air transportation is the safest mode of public transportation. Aviation safety has improved steadily over the past two decades. This is due to improved reliability of aircraft (made possible by technology advances in structure, materials, engines, electronics, etc.) and improvements in the other necessary parts of the system (air traffic control, communications, weather forecasting, etc.). On the other hand, the statistics also indicate that aircraft accidents attributed to human error continue to occur and imply that some of those accidents could have been prevented by the humans in the system.

Increased automation to reduce human workload and to augment human information processing and communication is altering the role of human operators in aviation, as well as in other high technology systems. However, evolving systems, while designed to be safer and more economically efficient than existing systems, actually could be less safe and efficient if the changing role of the human operator is not understood fully and planned for.

With the rapid growth of automation the human operator is becoming increasingly a supervisor of computers, which in turn directly control the machines. Thus, human abilities are being focused on the outermost control loops. However, while less human involvement is required for rote tasks, the human supervisor is being called upon to oversee more interdependent control loops, to allocate his attention among more displays, and to make more complex decisions.

While automation does not eliminate aircrew-vehicle interactions,* it does alter them in ways that may affect crew performance, and how

*Man-machine interaction refers to the communication with and control of machines by men. It is influenced by the art and science of designing display and control devices and workplaces, allocating functions between men and machines, and selecting and training operators and maintenance personnel.

that happens is not always understood fully. The need to determine the causes of error in current operations and to design future systems that will minimize the occurrence and effects of human error calls for a comprehensive research program drawing on all available resources, including those of NASA, FAA, DOD, industry, and academia.

While the human factors relating to "knobs and dials" cockpit design are pretty well established and documented in human engineering guides, principles of design for the new human-computer-aircraft interactions are in an earlier phase of development.

NASA and its predecessor, NACA, have been concerned with the human factors of aircraft control since very early in the history of aviation and in the 1950s initiated at the Ames Research Center a human factors research program that concentrated on pilot functions. NASA's current program--Human Factors in Aviation Safety--began in 1973. Today, the program is concerned with two areas--Flight Management and Simulation Technology.

The increasing awareness of the need to understand better the human side of man-machine interaction, and the awareness that research in human factors can improve efficiency as well as aviation safety, has led NASA to reexamine its program of research in this area. NASA's review has resulted in a proposed augmentation of its ongoing research program, to be focused on human factors in the aircraft cockpit. To assure that its planning is appropriate to the critical issues, NASA requested the National Research Council's Aeronautics and Space Engineering Board (ASEB) to evaluate its program. To accomplish the requested evaluation, the ASEB established the ad hoc Committee on Aircrew-Vehicle System Interaction. The committee was asked specifically to:

- o assess the appropriateness, relevance, adequacy, and timeliness of the program with respect to the needs and
- o provide recommendations regarding the objectives, approach, and content of the program plan.

To place the NASA program in context and to determine the degree of coordination and mutual support among the government agencies with responsibilities in aviation human factors, representatives of the Department of Defense (DOD) and the Federal Aviation Administration (FAA) attended the committee's meetings and the committee received briefings describing the DOD and FAA programs of research and technology development in the field of aviation human factors. The DOD and FAA programs are described in Appendix A.

The DOD effort is coordinated among the military services and NASA through the DOD Human Factors Engineering Technical Advisory Group (HFE-TAG) and its subgroups. The HFE-TAG consists of

technical representatives from the various organizational elements of the military services and NASA that have research and development responsibility in the area of human factors engineering.

The FAA recognizes that much of the human factors research and development needed to fulfill its responsibilities is addressed in NASA and DOD programs. Accordingly, the FAA draws upon the expertise and capabilities of these agencies, and there are a number of programs that are conducted jointly by NASA and the FAA's Office of Engineering and Development.

The ad hoc Committee on Aircrew-Vehicle System Interaction, which is responsible for this report, met at the NASA Ames Research Center, Mountain View, California on June 24-25, 1981 and at the National Academy of Sciences in Washington, D.C. on October 6-7, 1981.

ASSESSMENT OF NASA'S PROGRAM

NASA, recognizing the inevitable increased use of automated equipment in the aviation system to improve system capacity and economics, believes that this increased automation will affect the performance of pilots, air traffic controllers, and other human operators in unplanned and unexpected ways, not all of them desirable. In NASA's view, the data base on the capabilities and limitations of the human(s) in the system is inadequate, and there is no widely understood and accepted technology for the allocation of functions to man and machine. NASA predicts that, in the rush to apply the rapidly expanding new technology in electronics and avionics, insufficient attention will be given to the effects of automation on the human operator(s).

To provide the data base and technology it sees as required to avoid costly design and operating errors and possible hazards in future aircraft, NASA has proposed to augment its ongoing research effort in human factors. NASA's stated goal is to:

permit timely development of a human factors technology base to assist the aviation community in implementing more highly automated systems without incurring performance problems in the humans who must operate those systems.

The research program augmentation has been designed to build on the current ongoing program and to make use of as much past research and present knowledge as possible to develop new knowledge and technology through research in human factors.

The ad hoc committee agrees with NASA's assessment that the dramatic advances being made in microprocessor technology will produce an equally dramatic increase in automation of aviation systems. Consequently, the committee also shares the concern that sufficient attention may not be given to the effects of such automation on the human operator in the system, not because the operator is overlooked, but because adequate data on the effects of automation on human performance and thus on system safety are lacking.

The committee points out that the full range of human factors activity only recently has gained wide recognition as a valid technical field of design that is critically important to the conceptual design of the modern aircraft system. Because of its relatively recent acceptance, it has not yet developed the required coherent data base of technical information and applicable methodologies, as have the other areas of aircraft design such as aerodynamics, structures, and electronics. Thus, the need for research, not only to provide the information that will lead to improved designs, but also to predict, evaluate, and verify the value of the improvement. The committee observes that NASA is attempting to provide the leadership necessary to develop a data base and help establish direction for others in the field.

NASA has been involved in assessing man-machine interaction throughout the history of aviation. Recent major programs such as Short Take Off and Landing (STOLAND), Terminal Configured Vehicle (TCV), and the Aviation Safety Reporting System (ASRS) have been instrumental in identifying the nature and extent of man-machine interaction concerns associated with high-capability digital avionics. While identification of problems inherent in the application of new technologies is necessary to introducing them safely, problem identification alone is not enough. Rapid introduction requires an established knowledge base and validated assessment methodologies to permit timely and effective applications without incurring unreasonable risk.

The ad hoc committee reviewed and discussed NASA's program of research into the human factors aspects of the aircrew-vehicle system in two separate sessions. In the first session the committee reviewed NASA's ongoing program, and in the second session reviewed NASA's proposed program augmentation.

NASA's program is described in Appendixes B and C.

NASA's Ongoing Program

The committee's overall judgment of NASA's ongoing program is that the work being conducted consists of individual projects in which, although the projected results of each one will be valuable, a central guiding question or purpose to provide focus to the overall program is lacking. The committee believes that this situation can be corrected through redirection of effort in selected elements of the ongoing program to support the goals of the recommended program augmentation that is discussed subsequently. The committee recommends that NASA direct its program to providing the data base and methodology for measuring, understanding, and controlling human workload and predicting performance, including the understanding and prediction of human error.

NASA's ongoing program includes five elements: Flight Management Research, Simulation Technology, Aviation Safety, Workload/Performance Measures, and Human Response to Noise. Each of these elements is described in Appendix B. The committee's assessment of each element is included in the following paragraphs.

The Flight Management Research element of NASA's ongoing program appears to be appropriate, particularly those efforts dealing with the identification of types of human error, human decision making, and crew-error theories. The work on the cockpit display of traffic information will be of value so long as it remains focused on basic concepts.

The subelement "automation" is currently in an exploratory stage to define the problem area. It is intended as an introductory effort to support the proposed augmentation element, Man-Automation Function Allocation Strategies. Significant questions have to do with how to minimize crew boredom, apathy, and loss of skill, each of which is a cause of human error/failure. It is the committee's view that much of the effort planned for this subelement of the ongoing program is related to the understanding and avoidance of human error in future systems, and it is recommended that the work be planned and directed to support the proposed program augmentation element, Man-Machine Reliability Assessment Techniques.

The subelement "resource management" is an effort to improve aircrew performance by better definition and execution of the roles of crew members. The program originally was defined and initiated by NASA, and many airlines are adopting the results of the program. NASA's role now appears to be largely in refining techniques and providing information to potential users. This is an area in which NASA should be looking to others to assume responsibility for program continuity.

The "crew models" subelement is another effort that the committee believes would be of greater value applied to gaining a better understanding of human error.

The work under the Simulation Technology element could provide valuable data to enhance the utility of simulation as a tool for studying and clarifying man-machine integration problems. The three subelements currently under way or planned are aimed at improving understanding of what perceptual features are important or how to provide higher fidelity of simulated elements that are now believed to be important. More needed is investigation of the importance of the perceptual cues relative to one another and how they interrelate. With regard to perceptual fidelity, a distinction must be made between simulator characteristics suitable for training and those required for aircraft development research.

Experimental simulator requirements are considerably different from training simulator requirements. This is due to the fact that

the experimental simulators may be used to estimate the actual performance that can be obtained by the operational system. In this research and development application, high fidelity may be extremely important. The alternative to high fidelity simulation is actual flight testing of the system, which may delay decisions, make changes very expensive, and increase risks to test crews.

In contrast, much research suggests that very good transfer of training can occur with relatively primitive simulation and relatively low fidelity. Obviously, this will depend on the specific training objectives. Nevertheless, reliance on simulation for training of skills that are highly dependent on totally valid perceptual/motor cues is not a realistic objective because some cues, particularly sustained-motion cues, cannot be represented validly. Fortunately, there is no evidence that any specific sensory cues are uniquely essential to effective training. Although some factors potentially important in training, such as fear and the mental set associated with actually flying, may not be present, comparable stresses can be introduced through complex mission scenarios and automatically adaptive side tasks. Operational doctrine and procedures (particularly emergency procedures), effects of environmental variables, and fundamental skills already are being taught more effectively and economically in simulators than in their aircraft counterparts.

The focus of the NASA program in this area is considered too narrow. Very little is known concerning the relative weight of the various cues, e.g., how they interrelate and whether they modify behavior. Research on these fundamental questions would be valuable in many respects and would lead, ultimately, to a much superior and more cost effective simulation capability. It is recommended that NASA restructure the Simulation Technology program element to include research into sensory-perceptual-motor theory and define a more systematic long-term program. Hardware design, except for specific needs recognized as essential for fidelity of NASA research simulators, should be left to the manufacturers.

The Aviation Safety element consists of two subelements, circadian desynchronization and the aviation safety reporting system. Circadian desynchronization is an important problem, but the work should continue only if there is adequate support to undertake a systematic and comprehensive investigation of the many variables involved.

The aviation safety reporting system (ASRS) that NASA manages provides valuable data regarding certain incidents and near misses in the air system that otherwise would not become known since they do not result in accidents or otherwise reportable incidents. With a continuing awareness of the nature of the system and its shortcomings, the program is providing worthwhile data and should be continued.

The intent of the work being conducted under the element Workload/Performance Measures is to develop a valid, reliable methodology for measuring workload, particularly mental workload, to assist in understanding and evaluating man-machine interface concepts and designs, the goal being to assure that workload will be neither so high nor so low that the potential for error is increased. This has been a controversial and important issue that is generating a great deal of research in many agencies all around the world. No universal solution has been found and none may be for some time. NASA could make a valuable contribution by coordinating and providing focus for other researchers. The Defense Advanced Research Projects Agency (DARPA), military laboratories, universities, and overseas organizations are working intensively on this problem. It is recommended that NASA take the initiative and work with others in the field to establish a mechanism for coordinating the research being done to develop a reliable methodology for measuring physical and mental workload.

The committee considered the work being conducted under the element Human Response to Noise on the effects of aircraft noise on people on the ground, and concludes that it has little in common with the research activities in aircrew-vehicle system interactions. It is recommended that the work be removed from the aircrew-vehicle interaction program and conducted under another program category.

NASA's Proposed Program Augmentation

In its program augmentation, NASA proposes to identify gaps in existing knowledge concerning human interaction with automated aviation systems, to do the basic research to close these gaps, and to organize the results so as to be more useful to the aviation community. The knowledge gaps that require human factors research will be identified both through surveys and through evaluation of promising new models of the human operator.

NASA states that close liaison will be maintained with manufacturers, designers, the FAA, and DOD to ensure the usefulness and usability of the knowledge base generated in this program. The development of this knowledge base into quantitative models is one goal. However, the overriding goal is to understand why human errors are made, and to develop the data and methodologies to permit designers to create systems that minimize them.

NASA's goal is to improve the existing knowledge base of systems factors (hardware, software, procedures, etc.) that tend to induce human error. The objective will be to develop validated generalizable guidelines and not to develop hardware. Final validation of the guidelines to be developed will be accomplished in a few carefully selected flight tests. In those cases in which flight tests will be made, an attempt will be made to use systems

that the industry or the FAA has developed to a breadboard or prototype stage.

The program augmentation proposed by NASA and titled "Human Engineering of Automated Aviation Systems" comprise four elements:

- I. Man-Automation Function Allocation Strategies: to develop a technology base to aid systems designers in allocating functions to man and to machine and in selecting from alternative designs early in the development process.
- II. Man-Machine Interface Design Guidelines: to develop a technology base for choosing advanced displays and advanced input devices for effective information transfer between the operator and the system.
- III. Workload and Performance Measurement Methods: to develop methods for assessing crew workload and performance in a manual/automated environment.
- IV. Man-Machine Reliability Assessment Techniques: to develop methodology to assess overall reliability of the man-machine systems.

The first two augmentation elements, Man-Automation Function Allocation Strategies and Man-Machine Interface Design Guidelines, are intended to provide additional knowledge that can be used in selecting and designing future system functions in situations in which automation may play a major role in man-machine systems. The Man-Machine Interface Design Guidelines element focuses on methods of using advanced technology options to minimize information transfer problems. The second two elements, Workload and Performance Measurement Methods and Man-Machine Reliability Assessment Techniques, are intended to provide assessment tools and methods for evaluation of specific concepts.

Appendix C provides some detail regarding the planned content of each of the proposed program augmentation elements listed above.

Of the four elements of the proposed program augmentation, the committee concludes that NASA's effort should be concentrated on elements III and IV--Workload and Performance Measurement Methods, and Man-Machine Reliability Assessment Techniques. In the committee's judgment, these two critical elements are fundamental and well suited to NASA's capabilities. It is recommended that NASA incorporate in these two elements the tasks that are pertinent to them but, as presented to the committee, are included under the other two elements in the program as proposed and outlined in Appendix C. Further, it is recommended that the work be focused to providing the data base and methodology for accomplishing a predictive human performance failure modes analysis that could be

integrated with the methodology used for the failure modes analysis of hardware to provide a hazards analysis methodology for the overall system (man and machine).

It is the committee's judgment that the work on the development of methodologies and guidelines contained in elements I and II, Man-Automation Function Allocation Strategies and Man-Machine Interface Design Guidelines, should be concentrated on the development of principles and the development of methodology of general applicability, leaving its application and the formulation of specific strategies and guidelines to the industry.

The mental workload of both aircrew and ground controllers has emerged in recent years as a matter of concern internationally. This includes both sustained and transient demand levels, and interaction with stress, fatigue, crew-manning, procedures, air or ground allocation of functions, and other factors. At present there is little agreement on how to measure mental workload (e.g., whether by physiological indices, secondary tasks, or subjective scaling), but an understanding of the total task loading--mental and physical--as well as human limitations is essential to utilizing the contributions of both man and machine most efficiently and safely.

The question of crew size has arisen many times over the years in both civil and military aviation. The difficulty in dealing with the problem is compounded by lack of methodology and data stated in common scientific terminology that are reliable, organized, and in usable form.

NASA's proposed approach to the program element Workload and Performance Measurement Methods is empirical, involving a variety of pilots, aircraft types, and situations. Considering the limited understanding of the theoretical basis for cognitive processes, the experimental approach seems the most likely to produce timely usable results. This is considered to be an important subject and well suited to NASA capabilities. The work must be accomplished thoroughly and objectively if it is to achieve the acceptance and utility desired. The objectivity and broad scope of interests that NASA can bring to bear on this subject greatly increase the likelihood of success.

NASA should examine the effect of workload, particularly under stress, on the performance of the operator. Assessment of performance is a fundamental requirement for any total system evaluation. Improvement in the reliability of such measurement is very important. Assessment of workload is useful only if related to performance and performance breakdown. Methods of analyzing workload and performance to be obtained with alternative concepts would be especially useful in reducing design uncertainty and the need for redesign, resulting in a better product with reduced development cost in time and money.

The second recommended element, Man-Machine Reliability Assessment Techniques, as presented to the committee (see Appendix B, IV), was proposed as a subtask of the other three elements of the proposed program augmentation. The committee recommends this element be strengthened. What is needed is both study of man-machine reliability and study of how safety is affected by human performance.

Also, the word "assessment" generally connotes a limited activity, i.e., simply to predict and measure. In this instance, it should include methodology for prediction and measurement and development of remedial options.

To be more descriptive of the work the committee believes this element should include, it should be entitled: "Man-Machine Safety and Reliability Analysis Techniques: to develop methodology for analyzing overall safety and reliability of man-machine systems."

The committee believes that the subelements and research tasks required to provide the data base to permit a system-reliability assessment (including a human error hazard analysis) will constitute a comprehensive research effort. It will be generic in nature and will, ultimately, provide understanding of human error and the predictive design tool needed by aircraft designers and by the FAA for aircraft and airman certification.

This program element deals with two identified problem areas--prediction of human error and prediction of man-machine effectiveness. The program emphasis appears to be on assessment and evaluation, but it is important that the methodology be developed for use prior to the introduction of hardware as well as for analysis of operating hardware. Existing simulation, flight-test techniques, and operating hazard analysis provide the means for assessing man-machine systems once operating hardware is available. An intermediate goal of developing assessment techniques that depend on hands-on testing is reasonable, but a basic objective should be to develop methodology that can be used for prediction and application throughout a system's entire life cycle.

A subtask of this program element is adapting and developing theories of human error. An essential step in this process will be the development of suitable definitions of human error. NASA should involve a cross section of the aviation community in this task, thus assuring working definitions of error that will have broad applicability.

The final step in this element--that of evaluating the system-wide impact of human error--can provide an analytic means to establish the relative importance of various types of error. As such, it has significant potential for use as a preliminary design aid.

This portion of the proposed program augmentation has the potential to provide several new methodologies of broad applicability. Since most methodologies can be independent of specific device technology, the methods will be useful for both design support and evaluation and adaptable to industries other than aviation.

While extensive work has been done to delineate methods of analyzing and controlling hardware failures (reliability engineering technology), relatively little has been done to understand and predict human error in relation not only to the machine but also to man's total environment. It is important because failures and destructive accidents in systems are becoming more and more costly.

The revolution in air vehicle reliability and avionics systems reliability during the past ten years makes it important to establish quantitative data on man's reliability. To establish man's role in future aviation systems, his performance must be put into a form that is compatible with the equations used to establish the vehicle system reliability.

Current and next-generation aircraft can be considered to be transitional between man-dependent vehicles and fully automatic vehicles for many commercial and military missions. In future missions man may monitor/operate sensors while an automatic system flies the mission profile. A methodology for human performance failure and hazards analysis, and the data base required to develop it and to use it, will be needed to examine and define the function of man in order to determine for what functions human presence will be required in such a vehicle.

The insufficiency of available data is critical, and the lack of a framework within which the data may be used effectively is also critical. A methodology is needed for accomplishing a predictive human performance failure and hazards analysis that ultimately could be integrated with failure modes hazards analysis methodology used for hardware to provide an overall system (man and machine) hazards analysis methodology. In this connection, the use of such an analytic methodology should include provision for feedback of operational information to ascertain how systems are performing so that the hazards analyses can be improved and upgraded continually.

Human error deserves serious scientific attention. In the committee's view, human error is often misused as an alleged cause of accidents and it and its causes are little understood. The nuclear power industry just now is ordering that all operating plants do a complete system safety and reliability analysis including human errors (using fault trees, event trees, cause-consequence diagrams, and the like). NASA might well benefit by some strong liaison and technology transfer with that effort.

OTHER CONCERNS AND ISSUES

As stated earlier, the primary task of the ad hoc committee was to review and assess NASA's program of research in human factors directed to problems of aircrew-vehicle system interaction and recommend any changes considered necessary to enhance the effectiveness of that program. The results of the committee's review are contained in the preceding sections of this report.

During its review, the ad hoc committee exposed related issues that, although they have not been subjected to detailed analysis, it considered important enough to bring to the attention of NASA and others. These issues are briefly set out here.

Many incidents and accidents are determined to have been caused by human error and the committee judges it important to determine the cause of the human error. There is a dearth of information in cases involving human performance, and it is recommended that NASA explore the feasibility of establishing a program specifically to identify and evaluate the possible causes of pilot error in accidents and incidents deemed to be caused by human error and to identify how similar accidents and incidents can be avoided in the future. It is suggested that as a complement or extension of the Aviation Safety Reporting System (ASRS) project, NASA could pursue the investigation, analysis, and simulated re-creation of selected incidents and accidents involving crew-related causes or factors. The cases selected should be those in which the evidence available would suggest that the antecedent events leading to human error or errors might be expected to cause other pilots to make similar errors a high proportion of the time.

The air traffic control system invades the cockpit of commercial transport and general aviation aircraft in a major way and is a prominent element in the aircrew-vehicle system interface. As automation of the air traffic control system and of airborne systems increases, design of the aircrew-vehicle system interface becomes more complex. It raises questions such as: "Can pilots, with improved cockpit display systems, take on functions currently performed by the air traffic controllers on the ground?" "How will new display

technologies be applied?" To resolve these and other questions, better means are needed for modeling, testing, and predicting the effects of various alternatives on system efficiency and safety.

The committee also believes NASA should take a more holistic approach to experimentation, i.e., experiments should account for as many potentially critical variables as possible. Whatever their number, if critical variables are held constant in an experiment, unless the fixed values are close to those found operationally, findings can be grossly inaccurate when applied to operational situations. The use of economical multifactor experimental designs, pioneered by the chemical industry, can reduce the cost of aviation experiments and greatly improve the validity and generalizability of results.

APPENDIX A

SUMMARY OF OTHER GOVERNMENT PROGRAMS IN HUMAN FACTORS RESEARCH IN AIRCREW-VEHICLE SYSTEM INTERACTION

Department of Defense

The DOD R&D effort relevant to the interaction of the pilot/aircrew and the aircraft is conducted as part of a Training and Personnel Systems Technology (TPST) program, supervised by the Office of the Under Secretary of Defense for Research and Engineering.

The major elements of the program are:

- o Human Factors
- o Manpower and Personnel
- o Education and Training
- o Simulation and Training Devices

The work of interest to the ad hoc Committee falls under Human Factors and Simulation and Training Devices.

The total TPST program is funded at \$212 million in FY 1981, and \$265 million is planned in FY 1982. Over 59 percent of these funds are devoted to advance development and prototyping simulators and training devices. The areas of Human Factors, Manpower and Personnel, and Education and Training receive the remaining funds in approximately equal proportions. The reason for having such a large proportion of the research and development funds devoted to training is that DOD spends at least \$10 billion per year for training personnel and from \$1 billion to \$3 billion per year for equipment used in training. New high technology weapon systems are being introduced into the inventory at a time when there appears to be a severe lack of qualified personnel to operate and maintain them throughout their life cycle. This training need, now and in the future, is reflected in the major emphasis in the DOD program on simulators and training devices.

The distribution among the services, taking all funds into consideration (basic research through prototype development), gives

the Navy 56 percent, the Army 25 percent, and the Air Force 19 percent. However, if simulator prototyping funds are removed from the total, \$125 million were distributed in FY 1981--Army 38 percent, Navy 33 percent, and Air Force 29 percent. In FY 1982, the Army will receive 35 percent, the Navy 35 percent, and the Air Force 30 percent of approximately \$144 million. The Navy has the largest prototype development program in this area since they are only recently developing and using simulators for training in shipboard skills.

The DOD effort is coordinated among the military services and NASA through the DOD Human Factors Engineering Technical Advisory Group (HFE-TAG) and its subgroups. The HFE-TAG consists of technical representatives from the various organizational elements of each of the military services and NASA with research and development responsibility in human factors engineering.

The elements of the DOD TPST program that are directly related to NASA's program of research and technology development are Human Factors and Simulation Technology.

Federal Aviation Administration

The Federal Aviation Act charges the FAA with responsibility for assuring safe and effective use of the national airspace and for fostering civil aeronautics and air commerce. The FAA meets these responsibilities primarily through three major areas of activity:

- o Development, operation, and continuous improvement of the air traffic control system;
- o Promulgation of necessary regulatory action to assure that elements operating in the national airspace can and do operate safely;
- o Support and conduct of research and development required to improve the safety and effectiveness of operations in the national airspace.

Within the last several years, there has been growing recognition within the aviation community of the important link between better understanding of human capabilities and limitations and gains in the efficiency and safety of aeronautical operations.

In response to the 1975 DOT Secretary's Task Force Report on the FAA Safety Mission, the FAA undertook to enhance its work in safety and to establish a coherent, coordinated program, drawing on the work of the several cognizant FAA elements and on that of other government agencies (NASA and DOD). Under the direction of the Office of System Engineering Management, and with the support of FAA's Office of Flight Operations, Office of Aviation Safety, Air Traffic Service and Airways

Facilities Service, a program was initiated with the goal of aircrew and controller performance enhancement and error reduction. Programs were developed within a modest budget, utilizing primarily FAA and NASA resources, with emphasis on available resources and facilities within the government.

In late 1980 and early 1981, in part spurred by increasing emphasis on the issue of crew complement and crew workload and an increasing emphasis on automation, FAA held a series of government/industry/user workshops to gain additional perspective on the problem. These workshops resulted in recommendations ranging from general comments on program content and execution to specific research in experimental design methods.

Each of the efforts described above resulted in recommendations for additional work and more emphasis on the problem of human capabilities and limitations, which, it is conceded generally, constitutes the single most important cause of accidents and fatalities in aviation.

The FAA concludes from these efforts by industry and government that, while highly valuable work has been and is being done not only by NASA, DOD, and FAA, but also by industry and universities, there are fundamental issues of basic motivation and human capabilities on which valid scientific data are clearly insufficient and on which a great deal of research remains to be done. These are objective measures of workload; methods of reducing complacency, inattention, and boredom; and the design of a truly optimal balance between man and machine tasks.

The diversity of recommendations made to the FAA could be used to create a very extensive series of programs and activities relating to human capabilities and limitations. However, the FAA believes that its efforts should be confined specifically to its mission and responsibilities and should emphasize those efforts with directly traceable links to practical actions that can save lives. FAA believes it should follow progress in broader gauge, basic research and technical and scientific investigations and support them when they are perceived to be relevant. Such research should continue to be performed by the National Aeronautics and Space Administration, the Department of Defense, industry, and universities, with the support and collaboration of FAA:

Based on this rationale, the following research and development areas clearly have a component of human factors that must be considered by the FAA.

- o Research and studies to achieve more scientific human factors design guidelines, and criteria from the perspective of human capabilities limitations

- o Efforts to establish more effective skill, knowledge, and experience criteria for airmen training;
- o Development of better guidelines for operational procedures and system designs to achieve optimum aircrew/ATC interactions as new capabilities are introduced into aircraft and the ATC system;
- o Continuing analysis to identify areas in which research results can lead to improvements in safety or system performance.

Under its Aircrew Performance Enhancement and Error Reduction program (APEER), the FAA has a number of projects currently under way that address some of the issues in the above areas, some of which are cooperative efforts with the National Aeronautics and Space Administration. The APEER program has provided the nucleus for the Aircrew Human Factors program with a broadened range of concerns. Additional projects have been identified for inclusion in this new program, and more will be identified as the work progresses. Current or planned FAA and joint FAA/NASA projects are listed in Table 1. Projects independently planned by NASA and DOD are not shown. These projects are monitored by the FAA and relevant data and results utilized as appropriate in its program.

TABLE 1 FAA Engineering and Development Human Factors Program (Fiscal Year 1982/1983)

Project	Funding (\$1,000)
Pilot Workload Measures	784
Aircraft Alerting Systems Flight Phase Monitoring	836
Pilot Factors-Navigation	327
Collision Avoidance System Display Design Guidelines	270
Head-Up Display Flight Evaluation	522
Data Link Weather Information	99
Advanced General Aviation Display Certification Guidelines	--
Private Pilot Certification and Proficiency (Simulator)	242
Training for Improved Decision Making	291
Cockpit Data Management Requirements and Analysis (Evolving National Air Space)	200
Separation/Navigation Standards	--
Cockpit Display of Traffic Information	1,703
Commuter/Air Taxi Human Factors Problems	480
TOTAL	5,754

The FAA recognizes that much of the human factors research and development needed to fulfill its responsibilities is addressed in programs being conducted by other government agencies. Accordingly, the FAA has drawn and will continue to draw upon the considerable expertise and capabilities in those agencies, especially NASA and DOD.

The human factors staff and facilities of NASA are perceived to be especially critical to the success of the FAA program. Joint efforts such as the Cockpit Display of Traffic Information (CDTI) and Head-Up Display (HUD) projects are examples of such activity. Just as important are such basic research programs as flight deck automation, flight crew workload and performance assessment, and simulation technology. Also, NASA possesses extensive research facilities that can be used to evaluate various concepts such as line-oriented flight training (LOFT), thus minimizing the need for the FAA to develop new research facilities. Similarly, the basic and applied research being conducted by DOD in human engineering, system operation, and maintenance are important to the purposes of the FAA human factors program.

Through established coordination channels and interagency agreements, the FAA's Office of the Associate Administrator for Engineering and Development continually seeks to strengthen interrelationships with NASA and DOD to ensure that the expertise and facilities in those agencies are used as fully as possible in its aircrew human factors program.

APPENDIX B

DESCRIPTION OF NASA'S ONGOING PROGRAM

NASA's ongoing program includes five elements: Flight Management, Simulation Technology, Aviation Safety, Workload/Performance Measures, and Human Response to Noise. The program is carried on at the Ames and Langley Research Centers and the Dryden Flight Research Facility with a total of \$7.7 million in funding and 78 full-time civil service personnel in FY 1982. The 78 civil service personnel are augmented by students, grantees, and contractor and support personnel who are funded through this program.

Flight Management: NASA's goal in flight management research is to improve the scope and reliability of aircrew performance by providing a data base for optimum determination of crew roles, flight procedures, and control/display requirements.

There are four subelements; Cockpit Display of Traffic Information, The Role of Automation, Resource Management, and Crew Modeling.

- (a) Cockpit Display of Traffic Information (CDTI)--NASA is carrying out a program jointly with the FAA to assess the potential advantages and liabilities of CDTI. Work to date has been focused on developing a candidate display format and on part-task simulation evaluations of pilot ability to use CDTI for self-spacing and self-merging tasks. Upcoming work will focus on full-mission simulation studies in various scenarios so that workload assessments and possible detrimental effects of CDTI also can be evaluated.
- (b) The Role of Automation--NASA is beginning a research program to aid aircraft and air traffic control systems designers in allocating functions to man and to machine.
- (c) Resource Management--NASA seeks to develop methods of helping aircrews identify and apply the most effective human, technical, and mechanical resources to achieve safe, economical, and expeditious flight. Present work involves studying pilot responses to in-flight events, and

identifying resource management problems in commuter airline operations.

- (d) Crew Modeling--NASA seeks to describe pilot behavior in mathematically precise models. These models then are used to predict the effects of alternative cockpit and air traffic control system designs and procedures. In FY 1982, development of a Monte Carlo mathematical model that includes inputs to the crew members and probabilities of crew outputs for various situations will continue. Previous models have been used to describe the behavior of single crew members. The present model, dubbed "PROCRU," will describe the behavior of the entire crew. This model then will be used in testing the effects of various types and levels of automation on crew performance.

Simulation Technology: The goal of this work is to increase the capability of simulation for replacing active flight time in research, development, and training. Three subelements are included in the FY 1982 program: Motion/Visual Cue Substitution, Low Visibility Scene Generation, and Simulation Fidelity Assessment.

- (a) Motion/Visual Cue Substitution--Efforts here are to determine how much motion cueing can be effected using visual cues. A model of visual/vestibular cue interaction and a method of measuring "simulator motion deficit" (difference in motion between the aircraft and the simulator) are being developed.
- (b) Low Visibility Scene Generation--This work involves developing a model of fog and a method of evaluating candidates for simulation techniques.
- (c) Simulation Fidelity Assessment--A method for basing level of simulator fidelity in user needs has been developed and will be tested in FY 1982.

Aviation Safety:* The goal of this research is to identify deficiencies and discrepancies in the national aviation system as a basis for improving the current system and designing a future system. It has two subelements; the Aviation Safety Reporting System and Circadian Desynchronization (jet lag).

*It will be appreciated that the caption "Aviation Safety" as used here does not include all the work (most of the remainder of the NASA program) that contributes significantly to accident prevention and increasing accident survivability.

- (a) Aviation Safety Reporting System (ASRS)--The ASRS is an FAA-sponsored, NASA-managed incident reporting system. It is an anonymous, nonpunitive, voluntary, before-the-accident system in which anyone who witnesses an unsafe occurrence can file a report. NASA performs a number of data base searches and studies each year to detect trends.
- (b) Circadian Desynchronosis--This program is an attempt to quantify the effects of fatigue and circadian desynchronosis on aircrew performance and to develop ameliorative measures where necessary.

Workload/Performance Measures: The goal of this research is to develop improved techniques and methods for conducting empirical investigations into aviation human factors issues. During FY 1982, NASA plans to develop candidate measures for each of the components of workload (cognitive, psychomotor, and emotional) and evaluate their sensitivity to related factors such as age, experience, task demands, stress, fatigue, and type of aircraft. Alternative approaches to such evaluation include subjective reports and objective measures of eye scan, secondary task performance, and physiological correlates. In addition, NASA/Ames will be generating a practical guide for selecting and applying workload measures.

Human Response to Noise: The goal of this research is to minimize the effects of aircraft noise on passengers and on airport communities. There are three subelements of this research: quantification of single and multiple noises on the human ear, development of methods of assessing and minimizing the effects of aircraft noise on airport communities, and development of better understanding of how noise and vibration combine to affect passenger acceptance of aircraft ride quality.

NASA/Langley's aircraft noise synthesizer is the world's most advanced facility for studying the effects of aircraft noise on humans. Using this facility, a means for measuring the effects of aircraft noise on airport communities has been developed. The technique, called ALAMO (Airport Noise Levels Assessment Model), is being validated and is being evaluated for its ability to predict the decrement in noise effects derivable from varying aircraft approach and departure flight profiles. Other work on noise effects is being done on assessing the validity of time-of-day weightings in cumulative airport noise metrics and on assessing the combined effects of noise and vibration in various helicopters.

APPENDIX C

NASA PROPOSED PROGRAM AUGMENTATION HUMAN ENGINEERING OF AUTOMATED AVIATION SYSTEMS

The program augmentation proposed by NASA is comprised of four segments:

- I. Man-Automation Function Allocation Strategies
- II. Man-Machine Interface Design Guidelines
- III. Workload and Performance Measurement Methods
- IV. Man-Machine Reliability Assessment Techniques

A statement of the goal, the resources to be allocated, and a narrative description of the approach to be used to obtain the goal in each of the proposed program segments is contained in the following paragraphs.

It should be noted that in the NASA plan presented, the data necessary to accomplish segment IV are to be obtained from the research effort conducted under segments I, II and III.

I. Man-Machine Function Allocation Strategies

GOAL: Develop a technology base to aid systems designers in allocating functions to man and to machine, and in selecting from alternative designs early in the development process.

RESOURCES:

Fiscal Year	1983	1984	1985	1986	1987	1988
Funding (\$1000's)	1,950	2,350	2,000	2,000	2,400	2,400
Direct Man-Years	8	10	10	12	14	14

APPROACH:

- o Perform state-of-the-art review to develop heuristic design data base. The output will be a delineation of what is known and what is not known about human capabilities, limitations, and tendencies with automated systems. Investigation will not be limited to aviation, but will include other fields such as power generation, automobile manufacturing, and ground transportation, in which experience has been accrued with differential sensitivities of human operation to alternative automated system designs. As with the other data bases developed in this program augmentation, it will be made available to other researchers, the FAA, and industry.
- o Undertake research to close the knowledge gaps identified in the state-of-the-art review concerning the factors in automated system design that differentially affect human perception, cognition, and performance. The research results will be used to augment and refine models for predicting human performance in operating automated systems. The testing of these augmented models through simulation will in turn yield information on gaps in understanding that need further research. This iterative process will result in models that will contain the best available knowledge on the type, frequencies, and impact of human errors that specific design factors tend to induce. These then will constitute guidelines for the allocation of functions to man and to machine that will be validated through ground based simulation and ultimately flight test. These validated guidelines will be available for use by the industry in system design and by the FAA in certification and regulation.
- o A parallel effort will be undertaken to adapt "Knowledge Engineering" methodology to aviation. NASA then will develop guidelines for an integrated cockpit alert and warning system (ICAWS) and pilot-decision aids through:
 - (1) applying "knowledge engineering" methodology;
 - (2) applying the heuristic data base; and,
 - (3) basic research studies on human capabilities, limitations, and tendencies, with alternative design characteristics for those systems. This will result in guidelines for determining what planning and monitoring functions can and should be automated. These guidelines will be validated through simulation and finally through flight tests.

II. Man-Machine Interface Design Guidelines

GOAL: Develop a technology base for choosing advanced displays and advanced input devices for effective information transfer between the operator and system.

RESOURCES:

Fiscal Year	1983	1984	1985	1986	1987	1988
Funding (\$1000's)	350	1,000	1,350	1,700	2,200	2,700
Direct Man-Years	2	8	10	12	12	14

APPROACH:

Input Devices

- o Synthesize the state-of-the-art in human factors aspects of advanced input devices (keyboards, voice recognition, touch panels, etc.).
This study will summarize which human capabilities and limitations are important determinants of input-device performance as well as the gaps in our understanding of how the related design factors affect human performance.
- o Undertake basic human factors studies to close the knowledge gaps identified in the state-of-the-art. Use the resulting knowledge to augment and refine techniques to aid in the choice of input devices. The evaluation of the refined techniques will open further questions. The basic research will continue to address those questions throughout the program. The resulting techniques will allow designers to select suitable candidate devices for their systems based on the best available knowledge of the effects of input device characteristics on the performance of the human operator.
- o Develop guidelines based on the advantages and disadvantages of various input devices; validate guidelines through basic studies, simulation, and flight tests. The state-of-the-art data base and the techniques to be developed will be combined to provide guidelines on the selection of input devices.

Advanced Displays

- o Develop heuristic data base to aid in choosing displayed information and formats. Where possible, this study will synthesize previous experience into guidelines for display design, and will identify knowledge gaps concerning the effects of display design on human operator performance.
- o Develop guidelines and techniques for choosing symbols and display format through basic laboratory studies, simulation, and aircraft test. Laboratory studies and models will be used to further refine techniques for determining information requirements and choice of display formats.
- o Conduct research to determine human operator capabilities and limitations in using adaptive displays to develop guidelines for the design of displays that automatically adapt to changing conditions.

III. Workload and Performance-Measurement Methods

GOAL: Develop methods for assessing crew workload and performance in a manual/automated environment.

RESOURCES:

Fiscal Year	1983	1984	1985	1986	1987	1988
Funding (\$1000's)	800	600	600	600	600	300
Direct Man-Years	4	4	4	4	4	2

APPROACH:

- o Continue development of subjective workload component measurement techniques. Workload measures of man-in-the-loop conditions are required for evaluation of existing systems and for use with predictive efforts.
- o Develop predictive measures of cognitive and decision-making workload by adapting and expanding current manually administered workload measures. The resulting models can be used to predict workload as a function of task demands and operating environment so that workload can be assessed before actual simulation.
- o Develop objective measures of cognitive, decision-making, and resource-management performance of the crew through basic studies, simulations, and aircraft testing. These techniques will allow identification and quantification of the more important determinants of system performance.

IV. Man-Machine Reliability Assessment Techniques

GOAL: Develop methodology to assess overall reliability of the man-machine systems.

APPROACH:

NOTE: In the proposed NASA plan, the data necessary to accomplish this program segment would be obtained from the research effort to be conducted under the program segments I, II, and III as noted.

- o Synthesize the state-of-the-art for assessing manned system reliability; highlight omissions, and degrees of success in previous efforts. This study will pinpoint where further efforts will produce the most payoff (state-of-the-art synthesis from the heuristic data base element in program segments I, II, and III).
- o Undertake basic human factors studies to close knowledge gaps identified above. Adapt and develop promising theories of human error (theories of human error, is contained in the "human operator models" element of program segment I).
- o Develop techniques for evaluating the system-wide impact of human errors. The importance of human error is determined by the impact on overall system reliability; this program segment will produce techniques (e.g., simulation, tree analysis, hazard analysis) to evaluate the effect of human errors (error impact evaluation, is contained in program segments I and III).